Rare and Precision Frontier at the FCC-ee

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Rare Processes and Precision Frontier Townhall Meeting

Oct 2, 2020

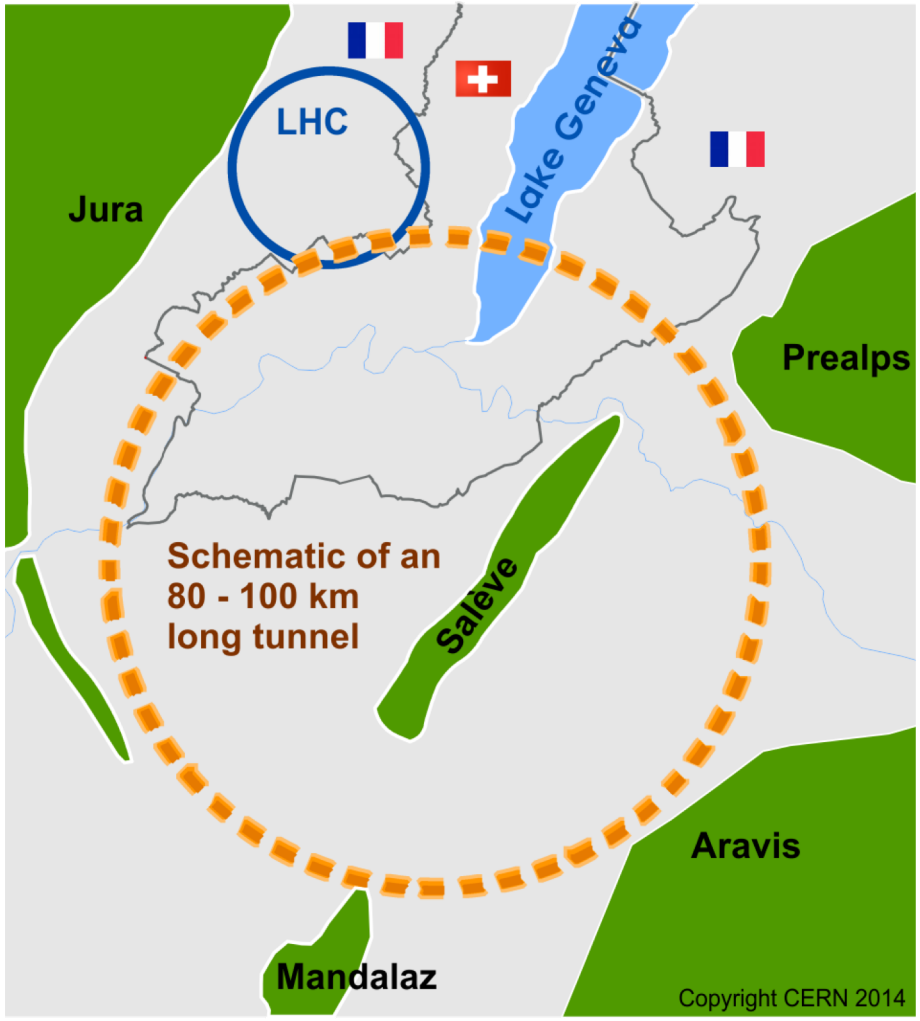
The European Strategy for Particle Physics

document

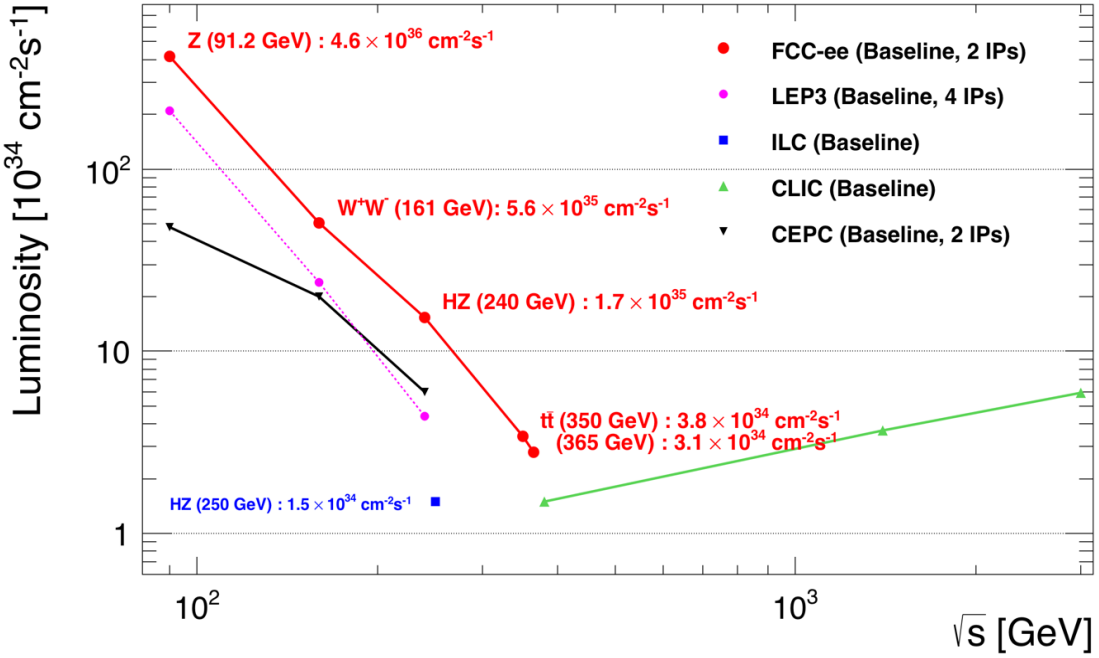
- An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. […]
- *Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavor […]*

What is the FCC-ee?

- A possible first stage for the FCC-hh
- An electron-positron collider
- 100-kilometer circular tunnel passing under Lac Leman at the border of France and Switzerland
- Shared infrastructure: The FCC-ee tunnel would provide a ready-made home for the FCC-hh.
- Beam energies range from about 44 **to 182.5 GeV** covering the Z-pole, W-pair threshold, ZH production and the top-pair production
- Double-ring collider with 2 (or 4) interaction regions and a booster synchrotron.



Energy range



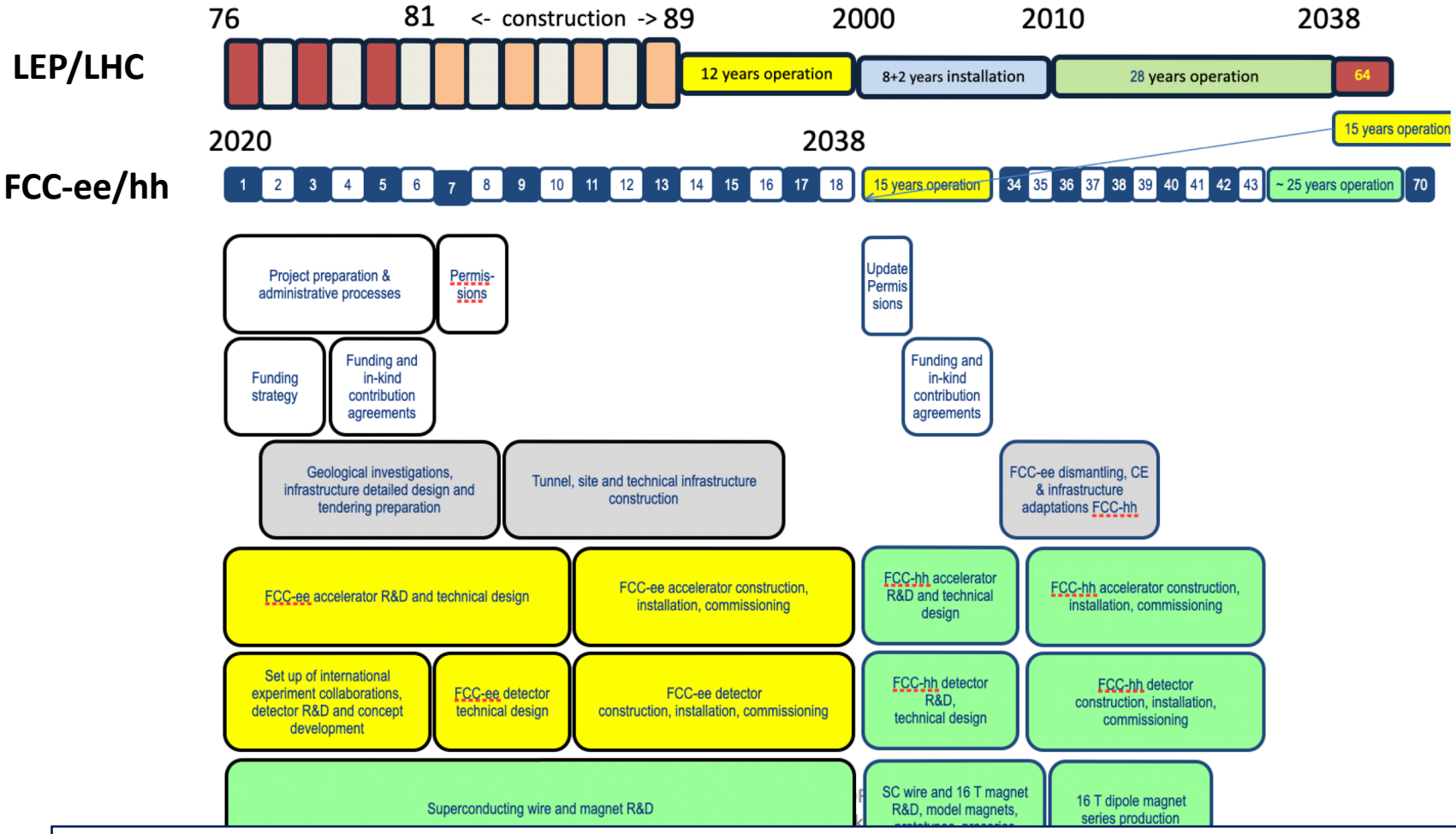
Great energy range for the heavy particles of the Standard Model

Complementarity with hadron (LHC, FCC-hh) and linear colliders

Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics
FCC-ee-Z	4	88-95	150	3×10^{12} visible Z decays
FCC-ee-W	2	158-162	12	10^8 WW events
FCC-ee-H	3	240	5	10^6 ZH events
FCC-ee-tt	5	345-365	1.5	10^6 $t\bar{t}$ events

LEP x 10^5
LEP x $2 \cdot 10^3$
Never done
Never done

Technical Schedule

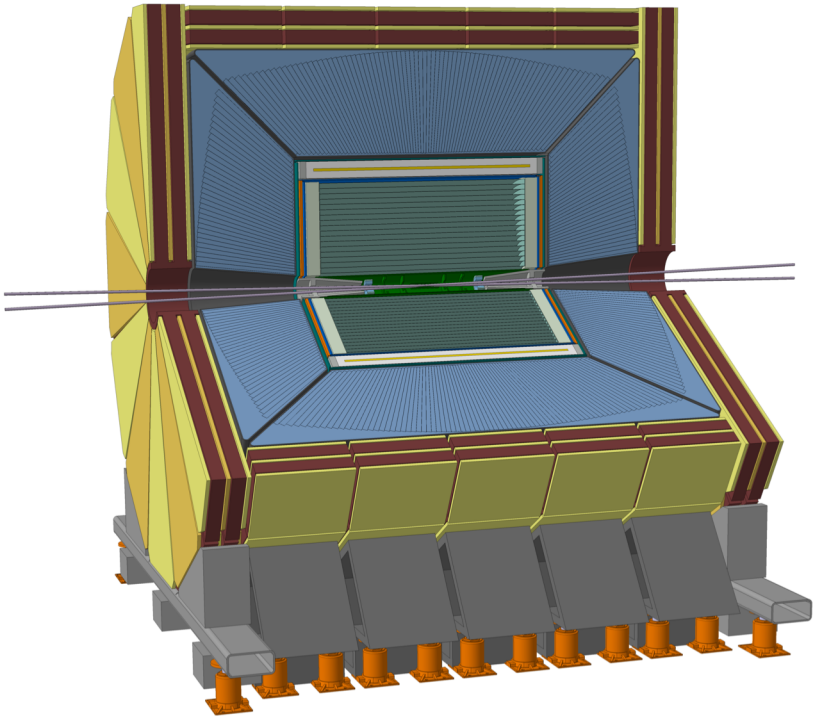


The FCC project plan is fully integrated with the HL-LHC and would allow for seamless continuation of high energy physics at the energy frontier

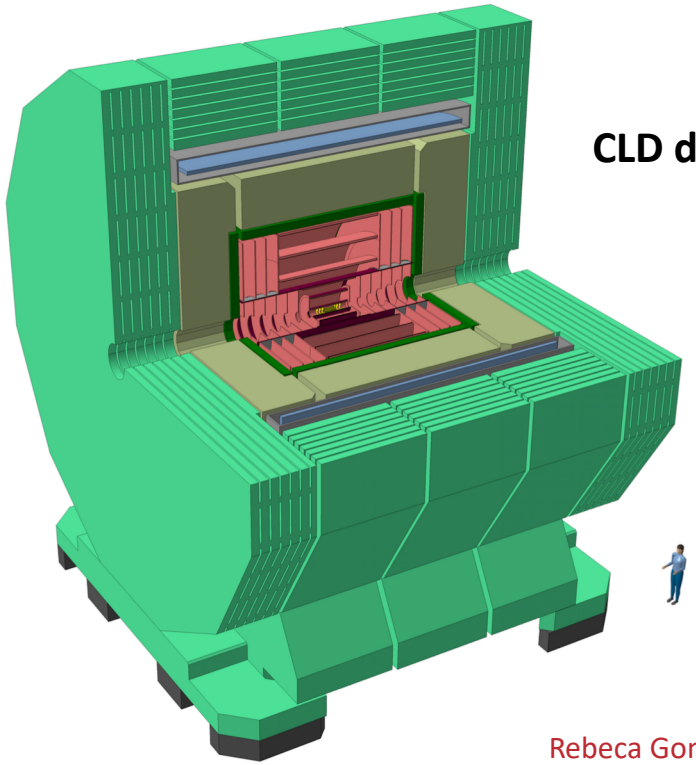
Detectors

Two detector concepts used for integration, performance, and cost estimates:

- One adapted for FCC-ee by the Linear Collider Detector group at CERN: CLD
- One detector specifically designed for FCC-ee (and CEPC): IDEA



IDEA design



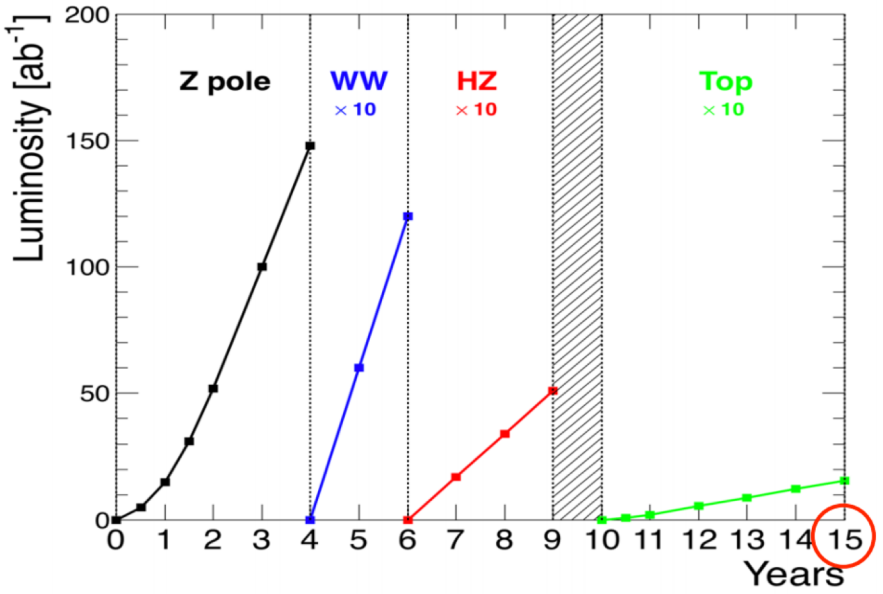
CLD design

Now: we are ready to take a broader look at the physics potential and optimize detector designs for complete physics program

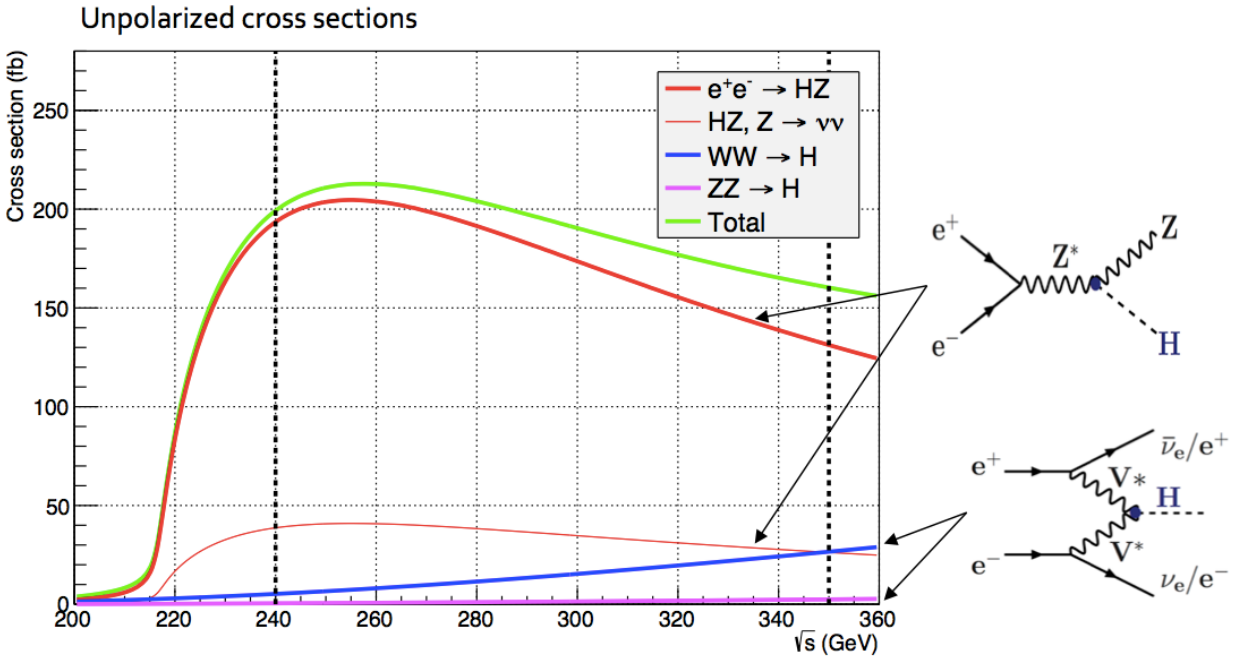
Opportunities to design multiple collider detectors

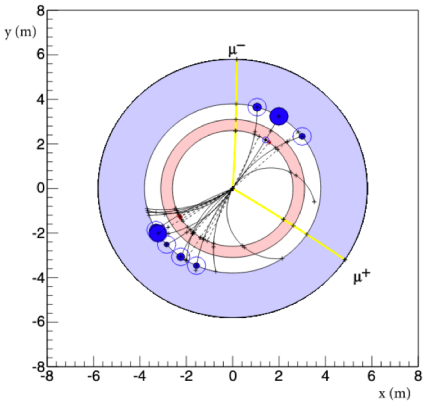
Physics Menu

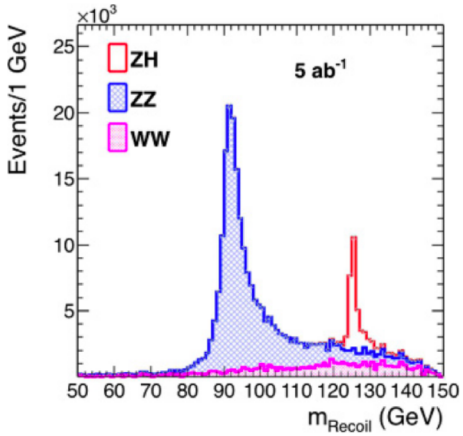
- The FCC-ee is a Higgs factory, but offers substantial additional physics options to explore
- Higgs factory
  - 10^6 $e^+e^- \rightarrow HZ$
- EW & Top factory
  - $3x10^{12}$ $e^+e^- \rightarrow Z$; 10^8 $e^+e^- \rightarrow W^+W^-$
  - 10^6 $e^+e^- \rightarrow tt$
- Flavor factory
  - $5x10^{11}$ $e^+e^- \rightarrow bb, cc$
  - 10^{11} $e^+e^- \rightarrow \tau^+\tau^-$
- Precision tool
  - α_{QED} and α_{QCD} (at m_Z^2), 10^5 $H \rightarrow gg$
- Direct new physics discovery
  - ALPs, RH ν's, …



Higgs physics at the FCC-ee



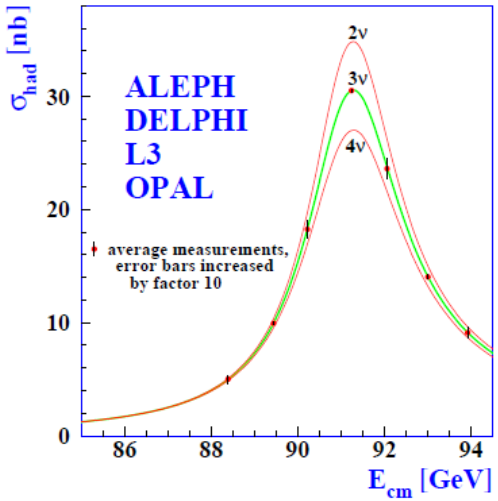




- Recoil method unique to lepton collider:
  - Tag Higgs event independent of decay mode
- Precision measurements: couplings, mass, width
- Searches for Exotic Higgs, invisible decays

Precision Electroweak Measurements

Z reconance: TeraZ



Lineshape

- Extremely precise E_{beam}
- m_Z, Γ_Z to < 100 keV (2.2 MeV)

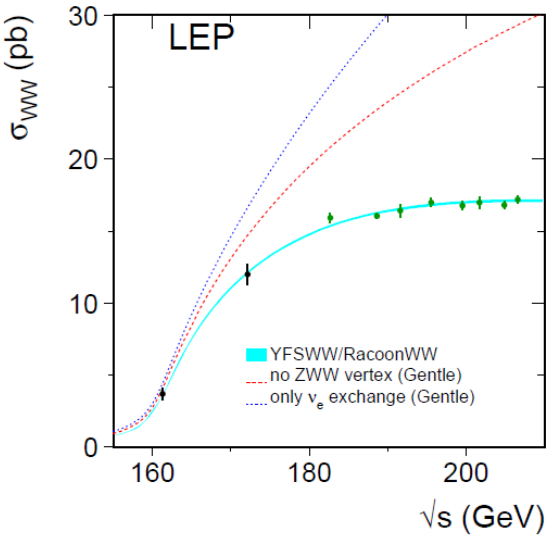
Asymmetries

- $\sin^2\theta_W$ to 6×10^{-6} (1.6×10^{-4})
- $\alpha_{QED}(m_Z)$ to 3×10^{-5} (1.5×10^{-4})

Branching ratios R_l, R_b

- $\alpha_S(m_Z)$ to 0.0002 (0.002)

WW threshold scan: OkuW



Threshold scan

- m_W to 0.5 MeV (12 MeV)

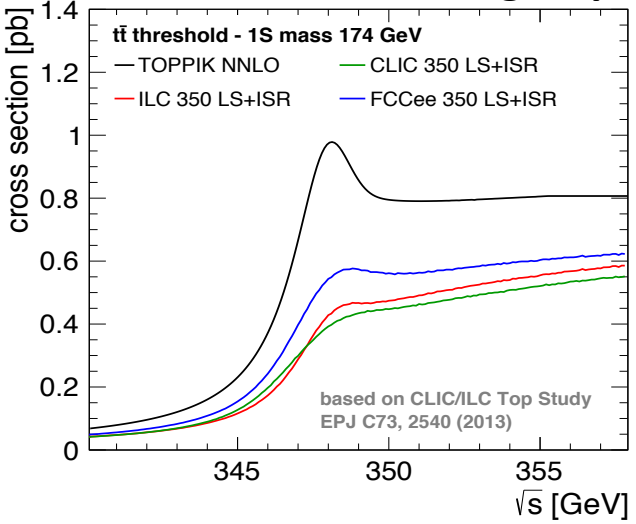
Branching ratios R_l, R_b

- $\alpha_S(m_Z)$ to 0.0002

Radiative return $e^+e^- \rightarrow Z\gamma$

- N_ν to 0.0004 (0.008)

tt threshold scan: MegaTop

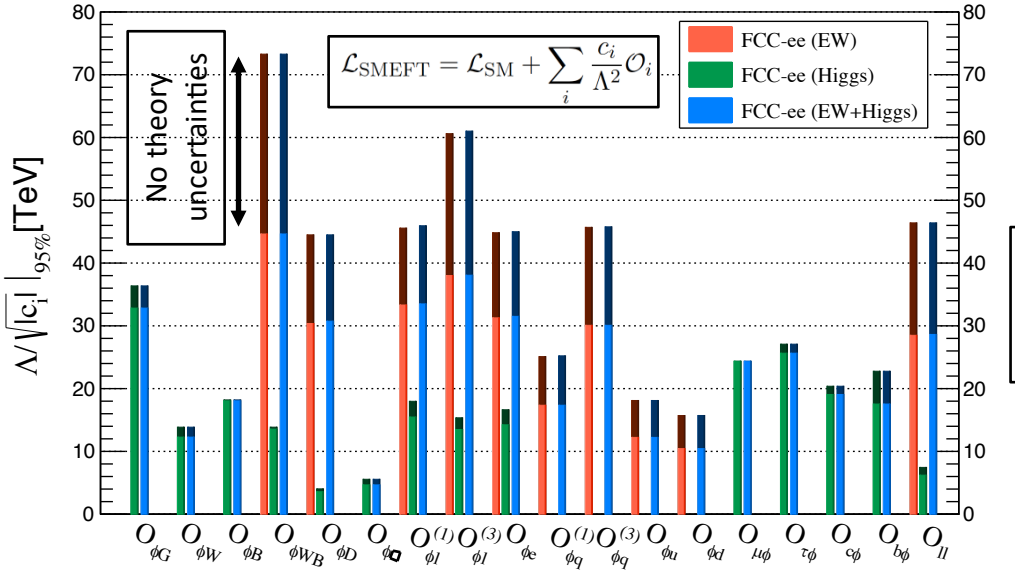


Threshold scan

- m_{top} to 10 MeV (500 MeV)
- λ_{top} to 10%
- EW couplings to 1%

Precision Measurement towards Discovery?

- Combining precision Higgs and EW measurements in SMEFT
  - Higgs and EWPO measurements are complementary (b,c,τ to be added)
  - EWPO are more sensitive to heavy new physics (up to 50-70 TeV)
    - Sensitivity was at the level of up to ~5 TeV at LEP
  - Larger statistics pays off for Higgs measurements
  - *Improvements in theory predictions will also pay off for EWPO measurements*



Deviating operators may point to new physics to be found by the FCC-hh

What about the rare processes and precision frontier?

Flavour at the Z pole

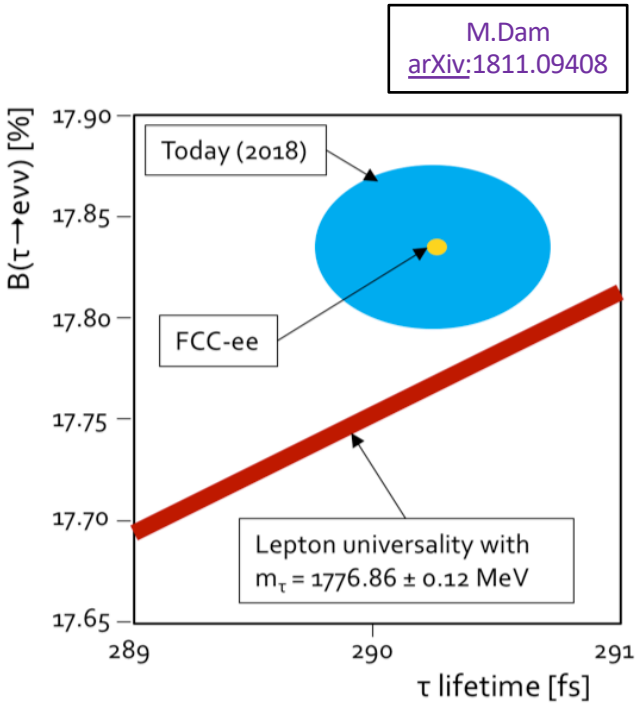
- All *b*-hadron species available
- Large tau production, boost
- Potential for excellent secondary vertex reconstruction
- Experiments at FCC-*ee* can cover the full program of LHCb & Belle II and compete favorably everywhere

	B^0	B^+	B_s^0	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield ($\times 10^9$) [for 5.10^{12} Z]	310	310	75	65	1.5†	600	180

† B_c hadronisation fraction assumed to be $f_{B_c} = 2.10^{-3}$.

τ physics

- Unprecedented statistics of boosted tau decay topologies
- Lifetime, branching fraction, mass measurements
- Highly competitive Lepton Flavour Universality tests



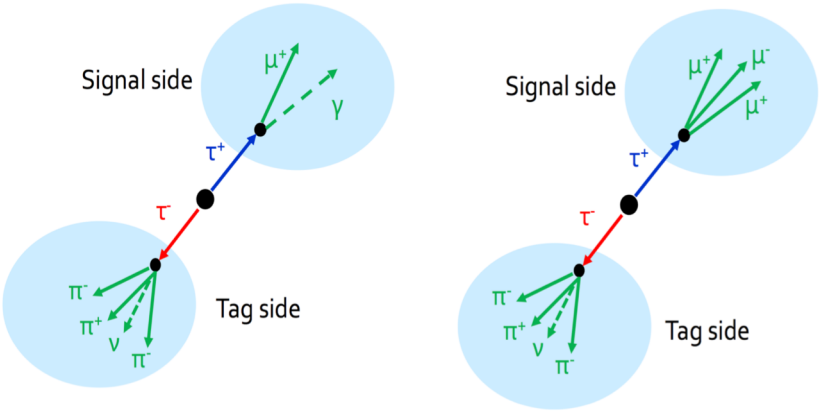
Property	Current WA	FCC-ee stat	FCC-ee syst
Mass [MeV]	1776.86 +/- 0.12	0.004	0.1
Electron BF [%]	17.82 +/- 0.05	0.0001	0.003
Muon BF [%]	17.39 +/- 0.05	0.0001	0.003
Lifetime [fs]	290.3 +/- 0.5	0.005	0.04

Conservative (esp. for mass):

- *small statistical uncertainties*
- *detector optimization to minimize systematic uncertainties*

Lepton-Flavour-Violating decays (tau decays)

- Benefits from large tau statistics and boosted topologies.
- Improved sensitivity of lepton flavour violation τ decays by 1-2 orders of magnitude
- Check the talk by Mogens in RF5: Charged Lepton Flavour Violation at the FCC-ee

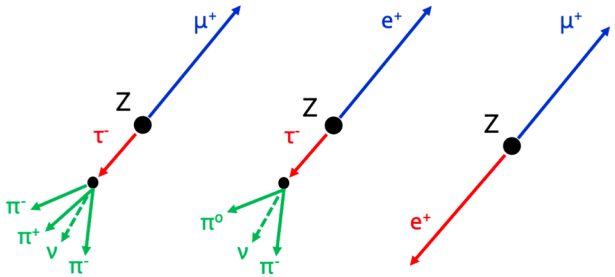


Decay	Current bound	FCC-ee sensitivity
$\tau \to \mu\gamma$	4.4×10^{-8}	2×10^{-9}
$\tau \to 3\mu$	2×10^{-8}	10^{-10}

Visible Z decays	3×10^{12}
$Z \to \tau^+\tau^-$	1.3×10^{11}
1 vs. 3 prongs	3.2×10^{10}
3 vs. 3 prong	2.8×10^{9}
1 vs. 5 prong	2.1×10^{8}
1 vs. 7 prong	< 67,000

Lepton-Flavour-Violating decays (Z decays)

Improved sensitivity of lepton flavour violationin Z decays



Current sensitivity to μe, $\tau\mu$, τe is around 10^{-7} , expected FCC-ee will go down two orders of magnitude

LoI

Snowmass2021 - Letter of Interest

Charged Lepton Flavour Violation at the FCC-ee

Thematic Areas:
- RF06: Charged Lepton Flavor Violation (electrons, muons and taus)
- RF04: Baryon and Lepton Number Violating Processes
- EF03: EW Physics: Heavy flavor and top quark physics
- EF04: EW Physics: EW Precision Physics and constraining new physics

Contact Information:
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Authors:
Alain Blondel[1], Mogens Dam[2], Patrick Janot[3], Stephane Monteil[4], Guy Wilkinson[5]

Abstract:
The FCC-ee is a frontier Higgs, Top, Electroweak, and Flavour factory. It will be operated in a 100-km circular tunnel built in the CERN area, and will serve as the first step of the FCC integrated programme towards $\geq$ 100 TeV proton-proton collisions in the same infrastructure [1]. With its huge luminosity at Z-pole energies, unrivalled samples of 5×10^{12} Z-decays will be produced at multiple interaction points. This opens up the possibility for very sensitive tests of charged lepton flavour violating (cLFV) processes in Z decays as well as in τ decays. For the Z-decay searches, where only limited progress has been made since LEP, three to four orders of magnitude improvement can be foreseen. This Letter of Interest describes some of the experimental challenges presented by these benchmark measurements.

[1]University of Geneva, Switzerland, and IN2P3/CNRS, France
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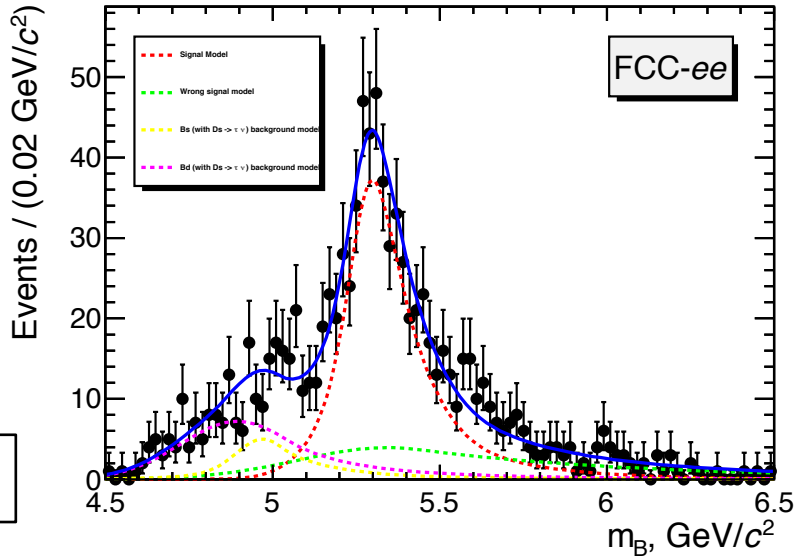
[3]CERN, EP Department, Switzerland
[4]CNRS/IN2P3), Clermont-Ferrand, France
[5]Oxford University, Oxford, UK

1

Flavour anomalies

- Measurements of the FCNC decays $b \to s\, l^+l^-$ show discrepancies w.r.t. the predictions consistently across experiments (Belle, LHCb and others) for $B^0 \to K^{*0}\, \mu^+\, \mu^-$
- The complementary decay modes $B^0 \to K^{*0}\, e^+e^-$ and $B^0 \to K^{*0}\, \tau^+\tau^-$ are important to interpret the discrepancies: likely unique at FCC-*ee*
- $B^0 \to K^{*0}\, \tau^+\tau^-$ requires partial reconstruction, *i.e.* the use of the production and decay vertices to solve the kinematics of the decay
- The SM branching fraction can likely only be attained at FCC-*ee*

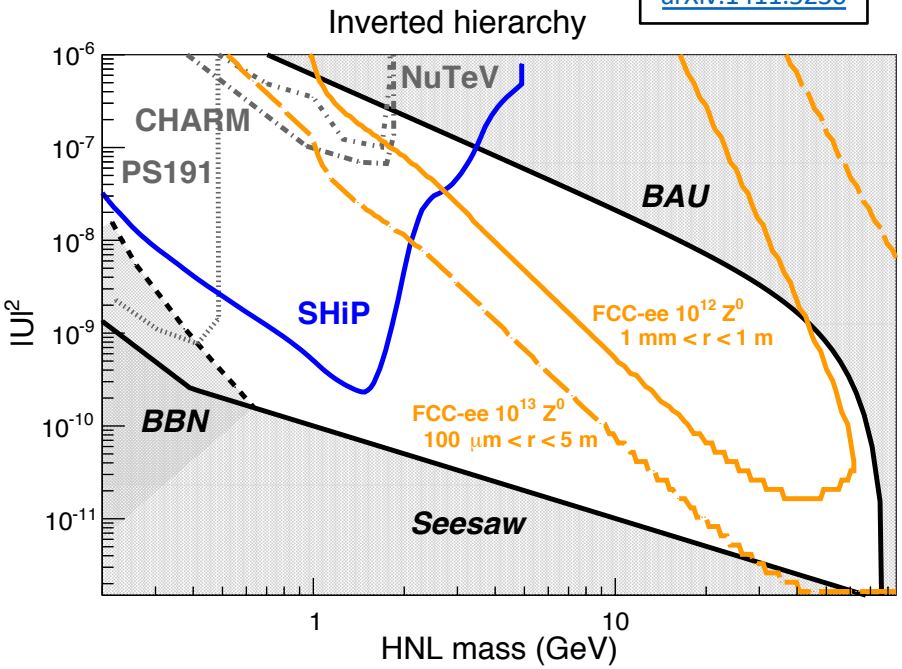
J.F. Kamenik et al.
arXiv:1705.11106



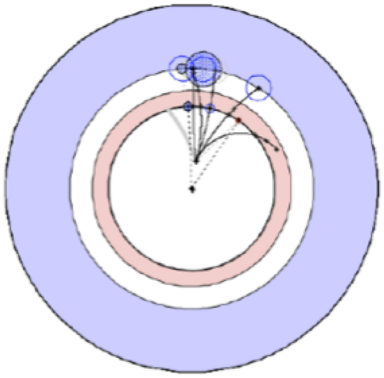
Direct discoveries

- Direct search of new, feebly interacting particles that could be either sound Dark Matter candidates, or closely linked to neutrino masses and the Baryon Asymmetry of the Universe and manifest long-lived signatures
- Flagship: **Heavy Neutral Leptons**
  - $Z \rightarrow \nu N$, $N \rightarrow l\, q^{-}q$
  - For low values of the neutrino mixing angle, the decay length of the heavy neutrino can be significant

A. Blondel et al.
arXiv:1411.5230

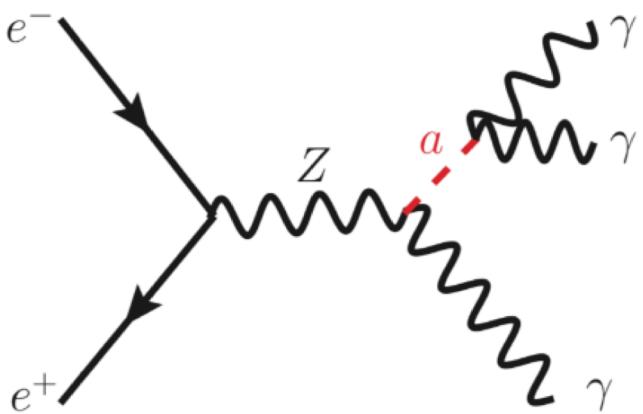


small mixing : long lifetime, displaced vertex



Direct discoveries

- light "Axion-Like Particles" (ALPs)
- very-weakly-coupled window to the dark sector



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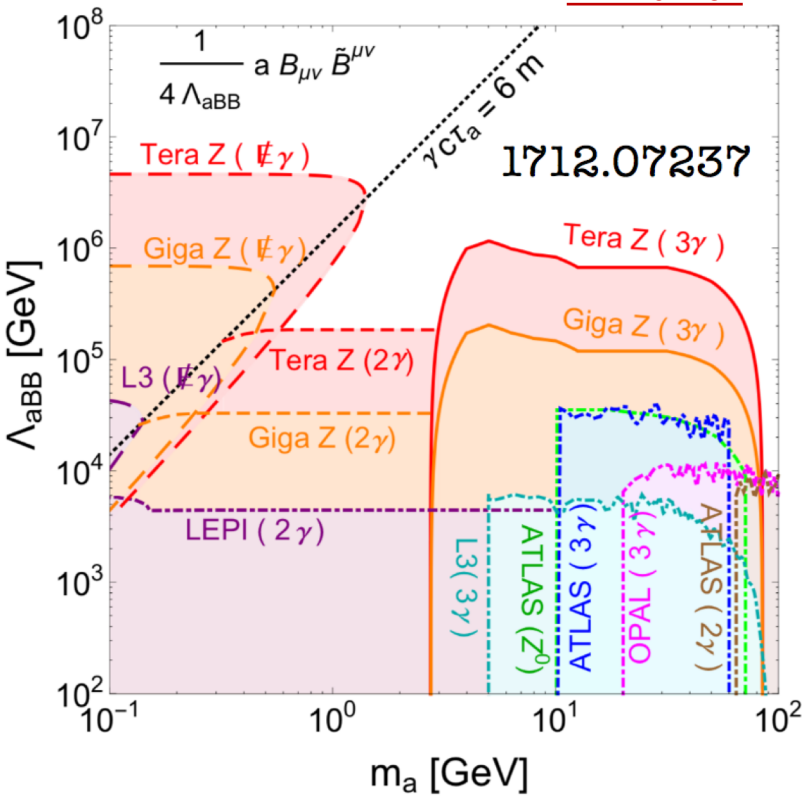

- γ + MET for very light a
- $\gamma\,\gamma$ for light a
- $\gamma\,\gamma\,\gamma$ for heavier a

- Orders of magnitude of parameter space accessible at FCC-ee

Long-lived particles at the FCC-ee

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Searches for Long-Lived Particles at the FCC-ee

Thematic Areas:

- (EF08) BSM: Model specific explorations
- (EF09) BSM: More general explorations
- (EF10) BSM: Dark Matter at colliders
- (RF6) Dark Sector Studies at High Intensities

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Authors: Patrizia Azzi [a], Alain Blondel [b], Rebeca Gonzalez Suarez [c], Caterina Doglioni [d] Elena Graverini [e], Gaia Lanfranchi [f], John Stupak [g]; Juliette Alimena [h], Marcin Chrzaszcz [i], Matthew Mccullough [j], Mogens Dam [k], Nicola Serra [l], Oleg Ruchayskiy [m], Oliver Fischer [n], Richard Brenner [o], Stefan Antusch [p], Wei Liu [q].

Abstract:
The FCC-ee is a frontier Higgs, Top, Electroweak, and Flavour factory. It will be operated in a 100 km circular tunnel built in the CERN area, and will serve as the first step of the FCC integrated programme towards $\geq$ 100 TeV proton-proton collisions in the same infrastructure [1]. In addition to an essential and unique Higgs program, it offers powerful opportunities for discovery of direct or indirect evidence for BSM physics, via a combination of high precision measurements and searches for forbidden or rare processes, and feebly coupled particles.

The direct search for Long Lived particles (LLPs) in the high luminosity Z run, with $5 \cdot 10^{12}$ Z produced, is particularly fertile; high statistics of Higgs, W and top decays in very clean experimental conditions will also be recorded. This motivates an out-of-the-box optimization of the experimental conditions, which is the object of this letter of intent.

[a] INFN, Padova, Italy
[b] UNIGE, Switzerland and IN2P3/CNRS, France
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[m] Niels Bohr Institute, University of Copenhagen, Denmark
[n] Liverpool University, United Kingdom
[o] Uppsala University, Uppsala, Sweden
[p] University of Basel, Basel, Switzerland
[q] Nanjing University of Science and Technology, Nanjing, China

- Both sterile neutrinos and ALPS show displaced signatures
- More models of new physics would produce long-lived particles at the FCC-ee
  - Twin-Higgs
  - Hidden Valley
  - Exotic Higgs decays …
- LLP studies at the FCC-ee offer many experimental opportunities
  - Detector design
  - Reconstruction algorithms
  - Many out-of-the-box

Summary

- Many opportunities to pursue within the rare processes and precision frontier
  - Z pole: **Large production of heavy fermions b, c, τ**
    - Boosted signatures, excellent e/μ/τ separation
    - Unprecedented statistics of boosted tau decays: precision measurements of mass, lifetime, and branching fractions
    - Improved sensitivity of lepton flavour violation (Z, τ)
  - High rates of B-hadron production will allow the FCC-ee experiments to allow to push further the B-physics program
    - Potential to shed light on flavor anomalies
  - New physics discovery opportunities (Dark Matter/Dark Sector)
    - Heavy Neutral Leptons, ALPs
    - Experimental-driven opportunities for Long-lived particles
- Study now to focus on laying out the optimization of detector design for the wide physics program

4th FCC Physics and Experiments workshop

4th FCC Physics and Experiments Workshop

10-13 November 2020
Europe/Zurich timezone

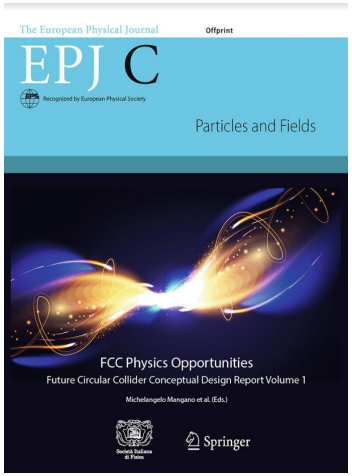
Search...

The 4th FCC Physics and Experiments workshop is part of the FCC Innovation Study Kickoff event, which will address the mandate issued by the update of the ESPP: *"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update."*

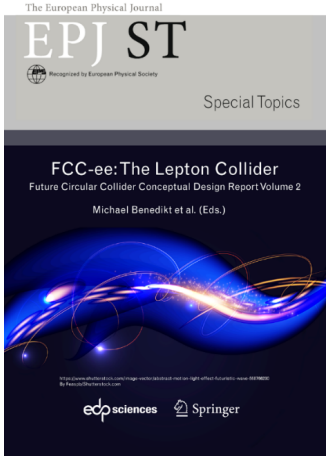
This new edition of the FCC Physics and Experiments Workshop will follow these strong strategic statements. It will feature the most recent results appeared in the literature on the study of the physics prospects of the Future Circular Collider project. On the experimental side, it will propose new activities aimed at the development of the detectors and collaborations for FCC-ee. Starting from physics benchmark measurements and the corresponding detector requirements, new ideas and challenges will be raised in the development of detector designs and technologies, of the experimental environment, and of the machine-detector interface.

Find out more: FCC documentation

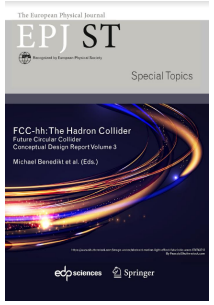
4 CDR volumes published in EPJ



FCC Physics Opportunities



FCC-ee: The Lepton Collider



FCC-hh: The Hadron Collider

HE-LHC: The High Energy Large Hadron Collider

- Future Circular Collider - European Strategy Update Documents
  - (FCC-ee), (FCC-hh), (FCC-int)
- FCC-ee: Your Questions Answered
  - arXiv:1906.02693
- Circular and Linear e+e- Colliders: Another Story of Complementarity
  - arXiv:1912.11871
- Theory Requirements and Possibilities for the FCC-ee and other Future High Energy and Precision Frontier Lepton Colliders
  - arXiv:1901.02648
- Polarization and Centre-of-mass Energy Calibration at FCC-ee
  - arXiv:1909.12245

- **FCC-ee Snowmass2021 LoIs:**
  - **https://indico.cern.ch/event/951830/**